Continuous and sequencing membrane bioreactors applied to food industry effluent treatment

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Abstract This work focuses on the performances of two immersed membrane bioreactors used for the treatment of easily biodegradable organic matter present in food industry effluents, for the purpose of water reuse. Two reactor functioning modes (continuous and sequencing) were compared in terms of organic carbon removal and of membrane permeability. For each working mode, pollutant removal was very high, treated water quality presented a low COD concentration ($<125\,mg.L^{-1}$), no solids in suspension and low turbidity (<0.5 NTU). The quality of the treated water (including germ removal) enabled its reuse on site. Moreover, by developing high biomass concentrations in the reactor, excess sludge production remained very low (<0.1 gVSS.gCOD^{-1}). The performances appeared slightly better for the continuous system (lower COD concentration in the effluent, $<50\,mg.L^{-1}$, and lower sludge production). In terms of filtration, a distinct difference was observed between continuous and sequencing systems; transmembrane pressure showed a small and constant evolution rate in continuous membrane bioreactor (CMBR) although it appeared more difficult to control in sequencing membrane bioreactor (SMBR) probably due to punctually higher permeate flow rate and modified suspension properties. The rapid evolution of membrane permeability observed in SMBR was such that more frequent chemical cleaning of the membrane system was required.

Keywords Membrane bioreactor; sludge reduction; water reuse

Water Science & Technology **Vol 56 No 2 pp 71–77** © IWA Publishing 2007

Introduction

Membrane bioreactors (MBR) are a relatively new technology in the wastewater treatment field. They are the combination of a biological reactor and a filtration step on porous membranes to separate biomass and treated water, thus replacing the settler used in conventional activated sludge systems. Unlike settling performance, the selectivity of the membrane barrier does not depend on sludge concentration in the reactor or biomass flocculation degree. This allows a high biomass concentration inside the bioreactor (from 8 to 20 g VSS.L^{-1}), leading to working under a high organic load rate, small footprint and low sludge production (Stephenson *et al.*, 2000). Another advantage of the use of membrane filtration is the great improvement in treated water quality, free of suspended solids, bacteria and viruses notably when working in the UF range (Ottoson *et al.*, 2006), thus leading to the possibility of direct reuse on site. Finally, because of the new MBR configuration including membrane modules directly immersed in the biological culture, the cost of the global system appears to compete favourably with conventional systems when the water is intended for reuse (generally requiring germ elimination).

In this context, the present work was carried out to compare the performances of two immersed membrane bioreactors with respect to effluent quality. The field of application was the food industry (including winemaking). Because the effluent production observable on industrial sites is not continuous, two functioning modes were chosen: (1) the first

doi: 10.2166/wst.2007.474

operates in continuous mode (requiring a separate basin for flow rate regulation upstream to the bioreactor); whereas (2) the second system was able to work in a sequencing manner to simulate a system capable of lineal effluent treatment on arrival at the wastewater plant. The former system is called a continuous membrane bioreactor (CMBR), and the latter is a sequencing membrane bioreactor (SMBR). Organic matter removal, sludge production and membrane permeability were examined and compared in this study.

Material and methods

Experimental set-up

The experiments were performed in two similar 50 L laboratory scale immersed membrane bioreactors (Figure 1). The size of the reactor was similar to the size of an oxidation ditch where the circulation of the suspension was generated by a horizontal rotating impeller. The system was continuously aerated to favour the development of aerobic cultures. The pH was maintained at 7.5 ± 0.5 and the temperature was regulated at $20 \pm 0.5\,^{\circ}C$. The dissolved oxygen concentration (DOC) was continuously controlled by a specific sensor.

Membranes

Polysulphone capillary membranes (2 mm in external diameter, 0.1 μm in pore size, initial membrane resistance 10^{12} m^{-1}) were packed inside each membrane module (Figure 1) directly immersed in the bioreactor. The filtration was conducted in an outside to inside mode. The permeate was collected inside the capillary fibres and extracted from the membranes by means of peristaltic pumps. A low and constant permeate flux was imposed in each MBR system, 2.3 and 7.2 $L.m^{-2}.h^{-1}$ for the CMBR and SMBR, respectively. Air was supplied by distributors placed at the bottom of the reactor, under each membrane module. The airflow rate provided oxygen to favour the aerobic biological process and induced shear stresses around the membrane modules to minimise reversible phenomena causing membrane fouling.

Substrate and culture

The wastewater used in this study was a synthetic substrate composed of a mixture of easily biodegradable compounds (acetate and meat juice) to obtain a global composition with an important fraction of soluble organic carbon and a low volatile suspended fraction. Such a composition can be representative of effluents from the food industry with a COD concentration close to BOD_{21}. This type of effluent may also be encountered when treating effluent from a previous anaerobic treatment step and requiring further refining by aerobic biological post-treatment. The average feed concentrations for both operations

Figure 1 Pilot bioreactor and membranes used for the experiments

are given in Table 1. A slight difference in total solid in suspension may be observed between the systems (less than 3% of the total COD).

Mineral salts such as ammonium nitrate ($(NH_4)NO_3$) and di-ammonium hydrogen phosphate ($(NH_4)_2HPO_4$) were added to maintain acceptable COD/N/P ratios and avoid any nutrient limitation.

The pH was controlled using $NaHCO_3$ at 0.5 $g.L^{-1}$ in the feed solutions.

Operating conditions in MBR systems

The systems were operated under the operational conditions given in Table 2. For the SMBR the cycle time was 12 h/cycle, with 0.3 h feeding time, 6.2 h reaction time, 5 h filtration time and 0.5 h resting time. Aerobic mixed cultures of heterotrophic organisms from a municipal wastewater treatment plant were used to inoculate the bioreactors. No sludge was removed from the pilot units, throughout the experimental period (except for sampling) to favour high biomass concentration.

The HRT concept is generally defined in the continuous system. Its introduction to the SMBR system means that the statistic liquid retention time in SMBR was equal to the value indicated in Table 2.

Analysis

The performance of the membrane bioreactors was studied by monitoring substrate degradation and biomass concentration evolution over time. Several parameters were determined in the influent, the effluent and the mixed liquor suspension. The supernatant was separated from the mixed liquor by filtering the biological suspension through 1.2 μm microfibre glass filters. The difference between the glass filters and the membrane pore size provides an evaluation of the small compounds present in the supernatant presenting a size close to the membrane pore and determining membrane fouling dynamics. The analytical methods are given in Table 3.

Results and discussion

Overall performance

Figure 2(a) and (b) shows the evolution of the COD concentrations during the operations in SMBR and CMBR, respectively. Some observations can be made:

- After several days of adaptation, high COD removal efficiencies were observed in both systems, with no presence of suspended solids and turbidity in the effluent. In the SMBR operation removal efficiency was over 94% during the last 20 days. In the CMBR system, removal efficiency appeared slightly higher. Acetate was not detected at any moment in the effluent, so the degradation of such easily biodegradable compounds was total. On the other hand, a light yellow colour remained in the effluent, probably due to the absence of biodegradable compounds in the meat juice.
- During the first period of both operations, a difference appeared between the soluble COD fraction in the mixed liquor (COD_{SR}) and the soluble fraction present in the permeate (COD_{TE}). This difference can be explained by the role of the membranes

Table 1 Mean concentrations of the feed solutions

	COD_{Total} ($mgCOD.L^{-1}$)	$COD_{Soluble}$ ($mgCOD.L^{-1}$)		$COD_{Particular}$ ($mgCOD.L^{-1}$)
		Acetate	Viandox®	Viandox®
Influent CMBR	1,830	1,500	284	46
Influent SMBR	2,090	1,500	514	76

Table 2 Summary of pilot-scale membrane bioreactors operating conditions

Operating condition	CMBR	SMBR
Working volume (L)	50	43–53.75
Hydraulic flow rate (L.d^{-1})	24	–
Feed flow per cycle (L/cycle)	–	10.75
Cycles per day	–	2
Volumetric organic load* (gCOD.L^{-1}.d^{-1})	1.0	1.0
Hydraulic retention time (d)	2	2
Temperature (°C)	20 ± 0.5	20 ± 0.5
pH	7.5 ± 0.5	7.5 ± 0.5
Dissolved oxygen (mg.L^{-1})	>2	>2

*respect to the minimal reaction volume in the case of SMBR

due to their specific retention with capacity with regard to macromolecules from 0.1 to 1.2 μm.

- This difference disappeared with time, which could be explained by biomass acclimation to these less biodegradable compounds, also observed as a gradual decrease in the soluble COD concentration in the permeate.
- In spite of the high COD removal efficiency observed, a higher COD concentration could be seen in the effluent from the MSBR (effluent COD concentration close to 125 mg.L^{-1}, except in the last 20 days) in comparison with the effluent from the CMBR (effluent COD concentration lower than 50 mg.L^{-1}). Therefore, reactor behaviour in a sequential mode appeared slightly less effective than in a continuous system, probably due to the instantaneous high organic load arriving during feed sequencing.

Nevertheless, the high values of removal efficiency demonstrated the capacity of the MBRs. The biomass retention time in the bioreactor was equal to the duration of the experiment because no sludge was extracted and the high value progressively reached enabled the growth of specific types of micro-organisms. The bacterial population thus included micro-organisms with very low specific growth rate (Rosenberger *et al.*, 2002) able to remove low degradable compounds. On the other hand, the presence of the membrane allows the retention of the solid phase and of some colloids that remain in the reactor for a period of time equal to solid retention time. These conditions are also favourable to some solid and colloid hydrolysis, contributing to reduced sludge production.

We also notice that the treated effluent was always free of suspended solids (no indication of suspended solids in the permeate); permeate turbidity remained lower than 0.5 NTU. This confirms the effective selectivity of the membrane barrier whatever the configuration. Germ removal was not evaluated during this study but the literature confirms the high membrane capacity to induce disinfection notably when operating in UF cut off (20 to 50 nm).

Sludge production

Figure 3 shows the development (no sludge extraction occurred) of MLVSS concentration inside both reactors during the operations. A relatively constant increase of MLVSS was

Table 3 Measured parameters and analytical methods

Parameters	Methods
COD_S, COD_T	Digestion method and colorimetric determination
MLSS, MLVSS	According to *Standard Methods* (1992)
Acetate	Enzymatic kit
Dissolved oxygen	Electrode oxymeter WTW oxi 340
pH	Hannah instrument pHmeter

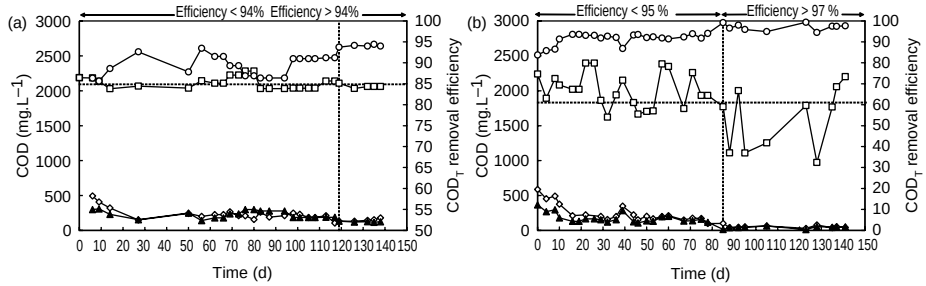

Figure 2 COD_{TI} (□), COD_{TE} (▲), COD_{SR} (◇) evolution and COD_T removal efficiency (○): (a) SMBR and (b) CMBR

observed despite the observation of cycles of growth and pseudo-stabilisation phases. During the overall operational period, the observed sludge yields were equal to $0.058\,gCOD_P.gCOD_T^{-1}$ and $0.092\,gCOD_P.gCOD_T^{-1}$ in the continuous and sequencing reactors, respectively. These values are approximately 5 to 10 times lower than those measured in the conventional activated sludge process (Pitter and Chudoba, 1990). The results clearly indicate lower sludge production in MBR systems. This may be considered a notable result since sludge conditioning remains a critical problem. About 60% of the total plant operating costs of a conventional wastewater treatment plant (WWTP) based on an aerobic treatment step, such as activated sludge, concern sludge conditioning and disposal (Davis and Hall, 1997; Horan, 1990).

The very low conversion yields obtained in the MBR, suggest that the substrate would be essentially consumed to ensure cell maintenance. Moreover, according to the successive increase and stabilisation cycles observed in the MLVSS evolution, some natural cell lysis phenomena could also occur. This phenomenon induces the release of metabolites that can be consumed by viable cells as a neo-substrate, ie cryptic growth (Lobos *et al.*, 2005).

The higher biomass production in the sequencing reactor may be due to biomass replication during the feed period (Lobos *et al.*, 2006) when the organic load was very high. Although the daily organic load was the same, the principal metabolic process appears to differ. More fundamental research would be required to understand such metabolic activity. In any case, slight sludge extraction from the system seemed necessary when working in a stable long-term operation in the membrane bioreactors. The overall performances of both systems are given in the Table 4.

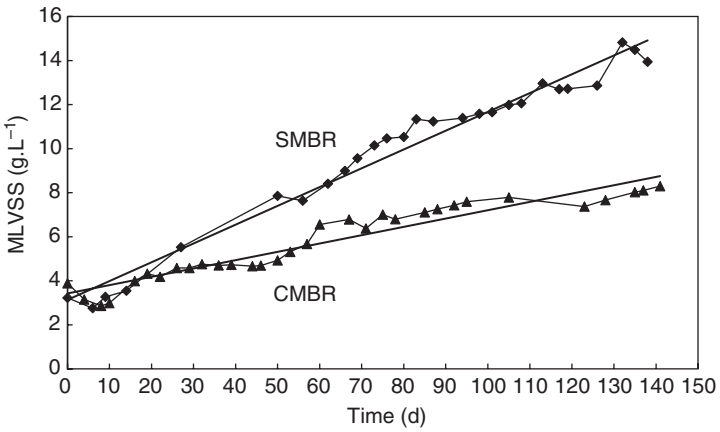

Figure 3 Biomass evolution (MLVSS): operation in SMBR (◆) and CMBR (▲)

Table 4 Overall performance of membrane bioreactors

Operating condition overall performances	CMBR	SMBR
Volumetric organic load ($g.L^{-1}.d^{-1}$)	0.92	1.04
COD effluent concentration ($g_{COD}.L^{-1}$)	<0.05	0.125
Organic matter removal rate ($g_{COD}.L^{-1}.d^{-1}$)	0.87	0.94
Biomass production rate ($g_{MLVSS}.L^{-1}.d^{-1}$)	0.04	0.086
Organic matter removal efficiency (%)	>97	>94
Biomass yield conversion ($g_{COD}.g_{COD}^{-1}$)	0.058	0.091
OUR stabilised value ($g_{O2}.L^{-1}.d^{-1}$)	0.50	0.86
Oxygen need ($g_{O2}.g_{COD}^{-1}$)	0.57	0.91

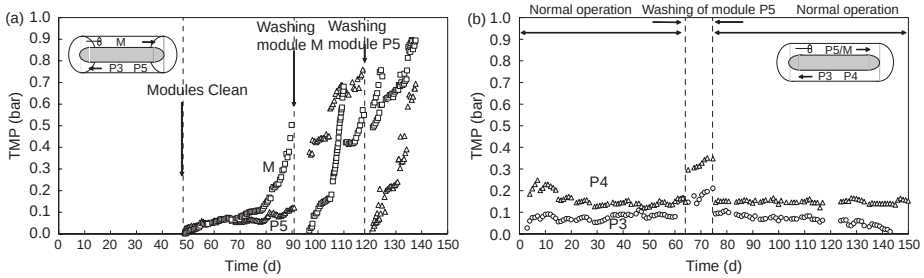

Figure 4 Transmembrane pressure evolution (TMP) of two membrane modules: (a) SMBR (operated at 7.2 $L.m^{-2}.h^{-1}$); and (b) CMBR (operated at 2.3 $L.m^{-2}.h^{-1}$)

Biomass activity. Despite the continuous increase of MLVSS concentrations, the respiratory activity measured by the oxygen uptake rate (OUR) was constant, implying that only a fraction of MLVSS was active in proportion to the organic load imposed on the system (Table 4). Nevertheless, the average value obtained in the SMBR system was seen to be 40% higher than in CMBR, possibly due to the sequenced feed procedure imposed on SMBR causing punctual high organic loading.

Filtration performances

Figure 4(a) and (b) shows the evolution of transmembrane pressure (TMP) on both modules immersed in each reactor, SMBR and CMBR, respectively. In the case of the CMBR modules (operated at 2.3 $L.m^{-2}.h^{-1}$), despite the continuous increase in MLVSS, membrane behaviour was nearly constant in Figure 4(b) and the hydrodynamic conditions avoided major fouling even at high MLVSS concentration.

This low permeate flux in the CMBR system, allows a filtration period of 3,600 hour without any membrane regeneration requirement. The performance of the third module of the CMBR system, operated at 4.6 $L.m^{-2}.h^{-1}$, was unstable and a washing procedure was applied. A temporary increase of the TMP of the other modules was observed.

Because of the higher permeate flow rate practised in the SMBR system (7.2 $L.m^{-2}.h^{-1}$ to compensate for the daily period without filtration), a higher fouling rate was observed. This phenomenon could also be due to the higher biomass concentration imposed (Figure 3) and to some other modifications of the suspension properties, e.g. viscosity.

Conclusion

Biological and filtration performances were investigated in immersed membrane bioreactors using a substrate mainly composed of an organic carbon soluble fraction. To simulate different working conditions, two working modes were compared: a continuous

mode and a sequencing mode. The results showed a high COD degradation performance and suspended solids retention for both systems (COD $<$ 125 mg/L and no SS detected in permeate) which would allow direct treated water reuse on an industrial site. A biomass adaptation period was necessary for the consumption of the less biodegradable fractions and the biomass conversion yields appeared very low compared with the values classically observed in the conventional process. Nevertheless, the results point to better performances with the continuous system notably in terms of controlling the filtration step. In the SMBR system transmembrane pressure evolution was greater than in CMBR and required more frequent membrane chemical cleaning.

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